

Mimicking diffuse supernova antineutrinos with the Sun as a source*

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Measuring the $\bar{\nu}_e$ component of the cosmic diffuse supernova neutrino background (DSNB) is the next ambitious goal for low-energy neutrino astronomy. The largest flux is expected in the lowest accessible energy bin. However, for $E \lesssim 15$ MeV a possible signal can be mimicked by a solar $\bar{\nu}_e$ flux that originates from the usual ^8B neutrinos by spin-flavor oscillations. We show that such an interpretation is possible within the allowed range of neutrino electromagnetic transition moments and solar turbulent field strengths and distributions. Therefore, an unambiguous detection of the DSNB requires a significant number of events at $E \gtrsim 15$ MeV.

I. INTRODUCTION

Neutrino astronomy and oscillation physics both began with the pioneering Homestake observations of solar neutrinos [1]. For a long time the now common interpretation of the solar neutrino deficit in terms of flavor oscillations was not unique and indeed the apparent time variation of the early data suggested magnetic spin or spin-flavor oscillations as an intriguing possibility in which Lev Okun took a keen interest [2, 3]. It was only the KamLAND measurements of reactor neutrino oscillations [4] that proved beyond doubt that such effects could not play a dominant role.

Today the frontiers of neutrino physics have shifted. The upcoming generation of flavor oscillation experiments involves long-baseline laboratory setups using reactors or high-energy beams as sources whereas one frontier of neutrino astronomy relies on high-energy neutrino telescopes. The new low-energy frontier includes solar neutrino spectroscopy and the search for supernova (SN) neutrinos [5]. While a high-statistics neutrino light curve from the next galactic SN would be a dream come true, in the meantime one may plausibly search for the cosmic diffuse SN neutrino background (DSNB) that is provided by all past SNe [6, 7, 8, 9, 10, 11]. In the energy range $10 \text{ MeV} \lesssim E \lesssim 30 \text{ MeV}$ the DSNB, with a total flux of order $10 \text{ cm}^{-2} \text{ s}^{-1}$, exceeds the atmospheric neutrino flux and other backgrounds and could provide interesting information on the stellar core-collapse rate and the corresponding neutrino spectra.

Cosmic redshift implies that the expected DSNB peaks at low energies and the largest number of events is expected in the lowest accessible energy bin. The only realistic detection process is inverse beta decay, $\bar{\nu}_e + p \rightarrow n + e^+$, so reactor $\bar{\nu}_e$ fluxes are an unsurmountable background below about 10 MeV.

We here study another background that can be important below about 15 MeV, the $\nu_e \rightarrow \bar{\nu}_e$ conversion of solar neutrinos [7]. In particular, we consider spin-flavor conversions that are induced by solar magnetic fields if neutrinos are Majorana particles and have sizeable electric or magnetic transition moments [12, 13, 14, 15, 16, 17]. While the old spin-flavor interpretation of the solar neutrino deficit would have required a conversion rate of order unity, here a subdominant effect of order 10^{-6} is enough to mimic the DSNB for $E \lesssim 15$ MeV. Such a conversion rate can be achieved without extreme assumptions about solar magnetic fields and within the allowed range of neutrino electromagnetic transition moments. The latter, of course, must be much larger than suggested by standard-model physics. If one takes this possibility seriously, the first events observed in the low-energy range can not be uniquely attributed to the DSNB unless there is enough statistics to reconstruct reliable spectral information.

To illustrate our point we begin in Sec. II with a brief review of the DSNB and its detection possibilities. In Sec. III we turn to the Sun as a source of antineutrinos due to the spin-flavor conversion mechanism. We discuss our findings in Sec. IV.

II. THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

The $\bar{\nu}_e$ component of the diffuse supernova neutrino background (DSNB) can be expressed as [8]

$$\frac{d\phi_{\bar{\nu}_e}^{\text{DSNB}}}{dE} = \frac{1}{H_0} \int_0^\infty \frac{dN(E_z)}{dE_z} R_{\text{SN}}(z) \frac{dz}{\sqrt{(z+1)^3 \Omega_M + \Omega_\Lambda}}, \quad (1)$$

where $E_z = (1+z)E$ is the neutrino energy at redshift z , E is the present-day neutrino energy, $N(E_z)$ is the $\bar{\nu}_e$ spectrum of an individual SN, $R_{\text{SN}}(z)$ the cosmic SN rate at redshift z , and $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ the Hubble constant. $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$ are the matter and dark energy density, respectively [18].

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To be specific we parametrize the cosmic SN rate in the form [8]

$$R_{\text{SN}}(z) = 4.1 \times 10^{-3} \text{ yr}^{-1} \text{ Mpc}^{-3} f_{\text{SN}} h_{73} \times \frac{e^{3.4z}}{e^{3.8z} + 45} \left[\Omega_{\text{M}} + \frac{\Omega_{\Lambda}}{(z+1)^3} \right]^{1/2}, \quad (2)$$

where f_{SN} is a normalization factor of order of unity and h_{73} is H_0 in units of $73 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

The average $\bar{\nu}_e$ spectrum emitted by a SN is expressed in the quasi-thermal form [19]

$$\frac{dN(E)}{dE} = \frac{(1+\alpha)^{1+\alpha} E_{\text{tot}}}{\Gamma(1+\alpha) \bar{E}^2} \left(\frac{E}{\bar{E}} \right)^\alpha e^{-(1+\alpha)E/\bar{E}}, \quad (3)$$

where we use $\bar{E} = 15 \text{ MeV}$ for the average energy, $\alpha = 4$ for the pinching parameter, and $E_{\text{tot}} = 5 \times 10^{52} \text{ erg}$ for the total amount of energy emitted in $\bar{\nu}_e$. The emitted spectrum is understood after all oscillation effects. The flavor-dependent differences of the antineutrino spectra emitted at the neutrino sphere are not large [19], so oscillation effects are not a major concern.

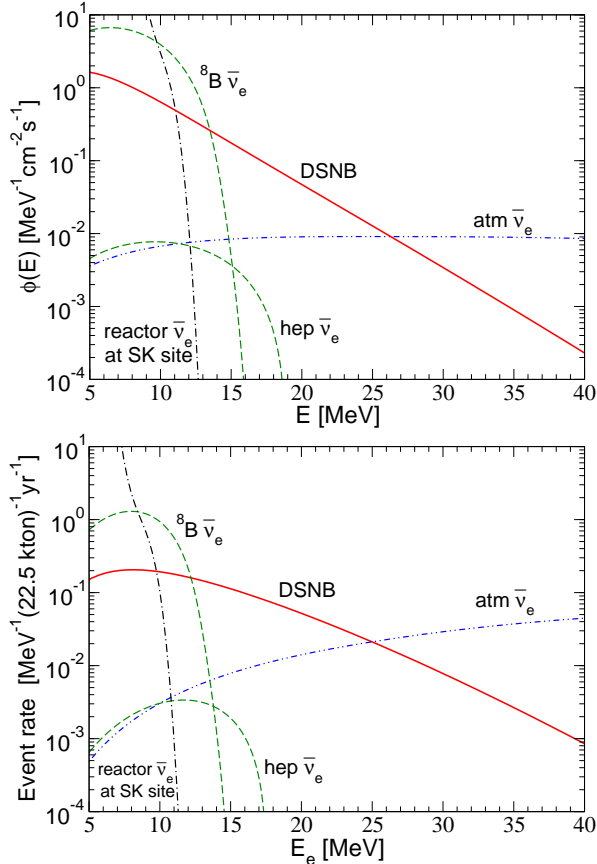


FIG. 1: $\bar{\nu}_e$ fluxes at the Super-Kamiokande site (upper panel) and positron event spectra (lower panel). The DSNB is an estimate for typical parameters (see text). The solar $\bar{\nu}_e$ fluxes correspond to the effective $\nu_e \rightarrow \bar{\nu}_e$ conversion probability of Eq. (4), i.e. 10^{-5} at $E = 10 \text{ MeV}$.

The $\bar{\nu}_e$ component of the DSNB calculated with these assumptions serves as our benchmark case and is shown in Fig. 1. The uncertainty in amplitude and spectral shape are considerable and we refer to the literature for a discussion [8, 9, 10, 11].

At low energies, the DSNB is overwhelmed by the background $\bar{\nu}_e$ flux from reactors. In Fig. 1 we show an estimate for the Super-Kamiokande site using an approximate analytical expression [20]. This flux significantly exceeds those expected at other possible locations that have been discussed, for example, by the LENA collaboration [21]. At high energies, the limiting factor is the atmospheric neutrino flux. The estimate shown in Fig. 1 is based on Ref. [22].

The only realistic reaction for detecting the DSNB is inverse beta decay $\bar{\nu}_e + p \rightarrow n + e^+$. Therefore, we show in the lower panel of Fig. 1 the same fluxes modulated with the cross section of this reaction, i.e., the expected event spectra. The largest number of events is expected in the lowest useful energy bin above the reactor background.

The most stringent upper limit is $1.08 \text{ cm}^{-2} \text{ s}^{-1}$ at 90% CL for $E > 19.3 \text{ MeV}$, obtained by the Super-Kamiokande experiment [23]. An actual detection requires tagging the final-state neutrons. In a large future scintillator detector such as the proposed LENA [21] neutron tagging is part of the detection signature. In water Cherenkov detectors, neutron tagging requires gadolinium loading [24], a possibility that is being investigated for Super-Kamiokande. Both detector types probably can lower the energy threshold all the way to the reactor background.

III. SOLAR ANTINEUTRINOS

If the detection threshold indeed can be lowered to the energy where the reactor background begins to dominate, the first DSNB events would be expected in the lowest energy bin above this boundary. In this range the solar ν_e flux from the ^8B reaction is more than five orders of magnitude above the baseline DSNB flux shown in Fig. 1. Therefore, even a $\nu_e \rightarrow \bar{\nu}_e$ conversion efficiency as small as 10^{-6} is enough to provide a significant background.

If neutrinos are Majorana particles and have non-zero transition magnetic moments, then solar electron neutrinos can oscillate to antineutrinos in the solar magnetic field [12, 13, 14]. Little is known about the interior B -field distribution in the Sun. We assume turbulent fields in the convective zone because they are well motivated and lead to the strongest conversion effect [15, 16].

For turbulent fields, a simple analytic expression for the $\nu_e \rightarrow \bar{\nu}_e$ conversion probability is [15, 16, 17]

$$P \approx 10^{-5} S^2 \mu_{11}^2 \left(\frac{B}{20 \text{ kG}} \right)^2 \left(\frac{3 \times 10^4 \text{ km}}{L_{\text{max}}} \right)^{p-1} \times \left(\frac{8 \times 10^{-5} \text{ eV}^2}{\Delta m_{\odot}^2} \right)^p \left(\frac{E}{10 \text{ MeV}} \right)^p \left(\frac{\cos^2 \theta_{\odot}}{0.7} \right). \quad (4)$$

Here $\mu_{11} = \mu_\nu/10^{-11}\mu_B$ (Bohr magneton $\mu_B = e/2m_e$) is the neutrino transition moment in a two-flavor scenario, whereas Δm_\odot^2 and $\cos^2\theta_\odot$ are the solar neutrino mixing parameters. S is a factor of order unity describing the spatial configuration of the magnetic field, B is the average strength of the magnetic field at spatial scale L_{\max} (the size of the largest eddies at which energy is pumped to generate turbulent motion), and p is the power of the turbulence scaling. A typical case is $p = \frac{5}{3}$ (Kolmogorov turbulence) whereas conservative values for the other field parameters are $B = 20$ kG and $L_{\max} = 3 \times 10^4$ km [16, 17].

Neutrinos with nonvanishing masses and mixings inevitably have nonvanishing electric and/or magnetic transition moments [25], which are however proportional to the neutrino masses and therefore extremely small. The best experimental limit on a neutrino transition moment connected to ν_e was found by the Borexino collaboration to be $\mu_\nu < 5.4 \times 10^{-11}\mu_B$ at 90% CL [26], while the best reactor limit is $\mu_\nu < 5.8 \times 10^{-11}\mu_B$ at 90% CL obtained by the GEMMA experiment [27]. An astrophysical constraint to avoid excessive energy losses by globular-cluster stars is $\mu_\nu < 3 \times 10^{-12}\mu_B$ [28, 29].

Using the benchmark values for all parameters as in Eq. (4) we show the expected solar $\bar{\nu}_e$ flux in Fig. 1. It is much smaller than the direct KamLAND limit on a possible solar $\bar{\nu}_e$ flux [30]. In the energy range above the reactor background and below the upper end of the solar ^8B spectrum, the solar $\bar{\nu}_e$ flux exceeds the DSNB by about an order of magnitude. A μ_ν on the level of the globular-cluster limit still provides a flux comparable to the DSNB. The true DSNB can be smaller than our benchmark by perhaps a factor of ten whereas the solar B -field parameters can be more favorable for spin-flavor oscillations. Therefore, it is clear that a first $\bar{\nu}_e$ detection in this energy bin can be caused by the Sun as a source instead of the DSNB.

In this case spin-flavor oscillations would also operate in the SN environment and thus affect the DSNB in that the neutrino and antineutrino source spectra would be partially swapped. This effect introduces an additional uncertainty in the DSNB prediction.

IV. DISCUSSION

Measuring the expected DSNB is a considerable challenge even with the next generation of low-energy $\bar{\nu}_e$ detectors such as a Gd-loaded version of Super-Kamiokande or a large-scale scintillator detector like the proposed

LENA. Our benchmark DSNB shown in Fig. 1 provides only a few events per year in a Super-Kamiokande sized detector, and the true flux can be even smaller. The expected spectrum decreases quickly with energy, so the largest event rate is expected in the lowest accessible energy bin, the reactor $\bar{\nu}_e$ background providing a hard lower boundary near 10 MeV.

Therefore, it is tempting to focus on the energy range directly above the reactor background. In this range, up to about 15 MeV, the solar ν_e flux is huge, about six orders of magnitude larger than the DSNB. Therefore, a small $\nu_e \rightarrow \bar{\nu}_e$ conversion rate is enough to mimic the DSNB in this energy bin. While such a conversion process violates lepton number, neutrinos with mass are usually thought to be Majorana particles and lepton-number violation is naturally present. A conversion probability on the 10^{-6} level is naturally found in the framework of spin-flavor oscillations if one assumes the presence of neutrino electric or magnetic transition moments on the level of existing limits and middle-of-the-road assumptions about solar turbulent B -field distributions.

Detecting a signature for lepton-number violation in the form of solar $\nu_e \rightarrow \bar{\nu}_e$ conversions arguably would be a more fundamental discovery than the DSNB itself. In this sense our arguments can be turned around and the DSNB can be viewed as a background to such a search.

Either way, disentangling the DSNB and a signature of solar $\nu_e \rightarrow \bar{\nu}_e$ conversion is extremely difficult except by enough statistics to provide spectral information above the endpoint of the solar neutrino spectrum. Directional information based on the neutron forward displacement in inverse β decay requires even larger event rates [31, 32].

The uncertainties of the interior solar B -fields are large and significant improvements on neutrino magnetic moment limits are not foreseeable. Therefore, a clear detection of the DSNB likely will have to depend on the energy range above the solar neutrino spectrum.

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